

MEASUREMENT OF HAND DYNAMICS IN A MICROSURGERY ENVIRONMENT:
PRELIMINARY DATA IN THE DESIGN OF A BIMANUAL
TELEMICRO-OPERATION TEST BED

Steve Charles, M.D. and Roy Williams
Center for Engineering Applications
Memphis, Tennessee

ABSTRACT

Data describing the microsurgeon's hand dynamics has been recorded and analyzed in order to provide an accurate model for the telemicrosurgery application of the Center's Bimanual Telemicro-operation Test Bed. The model, in turn, will guide the development of algorithms for the control of robotic systems in bimanual telemicro-operation tasks. Measurements were made at the hand-tool interface and include position, acceleration and force between the tool-finger interface. Position information was captured using an orthogonal pulsed magnetic field positioning system resulting in measurements in all six degrees-of-freedom (DOF). Acceleration data at the hands was obtained using accelerometers positioned in a triaxial arrangement on the back of the hand allowing measurements in all three cartesian-coordinate axes. Force data was obtained by using miniature load cells positioned between the tool and the finger and included those forces experienced perpendicular to the tool shaft and those transferred from the tool-tissue site. Position data will provide a minimum/maximum reference frame for the robotic system's work space or envelope. Acceleration data will define the response times needed by the robotic system in order to emulate and subsequently outperform the human operator's tool movements. The force measurements will aid in designing a force-reflective, force-scaling system as well as defining the range of forces the robotic system will encounter.

All analog data was acquired by a 16-channel analog-to-digital conversion system residing in a IBM PC/AT-compatible computer at the Center's laboratory. The same system was also used to analyze and present the data. It is anticipated that the data will also provide needed information for other tasks to be explored at the Center. These include telemicrosurgery in remote locations such as space, telemicroassembly of computer, electro-optical and small mechanical systems, telemicromanipulation of miniature sensors and telemicrohandling of hazardous material.

INTRODUCTION

Procedures in the medical, biological, industrial and military fields are continually being down-sized. It is not uncommon for the microsurgeon to perform 150 to 200 micron movements during an operating procedure. In many cases the dextrous microsurgeon would like to be able to decrease these movements (1-10 microns for operation on small vessels near the retinal surface or inner ear) but cannot due to the limits of human dexterity. For those surgeons where dexterity is absent (old age or inexperience) but the expert knowledge exists, a means for improving that dexterity must be

explored. Likewise, as the experimental biologist explores further and further into human anatomical structures and physiological processes (for example, manipulation of 1-10 micron patch clamp sensors), the need for smaller handling systems and exact placement of micro-instrumentation sensors arises. Finally, with the emergence of microsensors and microdynamical systems (MDS - mechanical devices and systems fabricated on silicon) assembly and inspection becomes a micromanipulation task since these devices are typically on the order of 20-200 microns [1]. These tasks will push the limits of human dexterity just as seen in the microsurgery field.

The Center for Engineering Applications (CEA) has begun design and development of a Bimanual Telemicrorobotics Test Bed featuring high-precision robotic manipulators to address these dexterity needs. This paper's primary focus is on preliminary data describing the microsurgeon's hand dynamics. These measurements and the test bed concept and their benefit to NASA space telerobotics will also be explored.

We feel the benefits exist in three primary areas. First, the concept of telemicro-operation for microsurgery can be extended to remote locations just as current work with telerobots for the Shuttle Remote Manipulator System and the Space Station systems. For extended missions an on-board surgery capability can eliminate the costs of returning the injured crewman to earth or delivering the microsurgeon to the patient site. Secondly, we feel the surgeon-machine interface (SMI) we are currently developing will aid NASA in eliminating some of the dexterity problems currently encountered in pressurized spacesuits. The interface will be small enough to fit within the spacesuit allowing the astronaut to manipulate tools attached to the end of the spacesuit arm. This will enable the astronaut to remain at the site (as opposed to manipulation within the base vehicle) for those operations in limited access areas. Finally, the test bed may also be used to manipulate samples in experiments best done in the gravity-free environment. The Space Shuttle has already performed such experiments and proven the concept. The test bed can further that ability by allowing down-sized manipulation of such samples (viral strains, microelectro-optics, micromechanical systems, etc.).

EXPERIMENTAL APPARATUS

All data was collected in the surgical environment using a Northgate PC/AT-compatible system as the host. This system operates at 12 MHz, has 1 MByte of RAM, an 80287 math co-processor and a 60 MByte hard disk. Position information was acquired using the Polhemus 3SPACE Isotrak system. The Isotrak connects to the host via a serial link capable of 19.2K baud. With data averaging incorporated position updates occur every 35.7 msec where translational resolution is 0.762 mm RMS and rotational resolution is 0.12° RMS. The Isotrak source was mounted on and above an aluminum tripod with the sensor mounted on the selected operating tool. The sensor weighs approximately 23 grams and did not adversely affect the surgeon's operation (there was some limitation due to the data cable and physical dimensions of the sensor and is discussed in the Methodology section).

Acceleration data was captured using a Vibro-Meter triaxial accelerometer (model CE505M201) connected at the back of the surgeon's hand. The accelerometer has a sensitivity of 10 mV per g at $\pm 10\%$ with a frequency response of 2 Hz to 15 kHz at ± 3 dB. The unit requires 15 V at 0.5 mA and was powered by a temperature compensated battery power supply. This device weighs 10 grams and also requires a cable for power and data transmission.

All force data was recorded with A.L. Design's model ALD-Micro-1 Load Cell which uses a full four arm internal Wheatstone bridge using bonded strain gages. Two cells were used to record data simultaneously. Each cell has a full scale operating range of 450 grams and features a combined error (linearity, hysteresis and repeatability) of $\pm 0.5\%$ FS. The total range of force was reduced for our experiment thus reducing this error. Each cell requires 5 Volt excitation at about 15 mA which was supplied again by a temperature compensated battery supply.

All analog data from the accelerometers and force transducers was digitized using a MetraByte DAS-16F A/D converter board residing in the host PC. This board uses a 12-bit successive approximation converter capable of 100 kHz conversion rates. It features 8 differential channels (90 db CMR) and is software programmable for conversion timing. The input features a high input impedance instrumentation amplifier with switch selectable gains. Output of both the accelerometer and the force transducer was quite low (tenths of mVolts) and thus external amplification was used. Three Tektronix AM502 Differential Amplifiers were used as buffers between the transducers and A/D converter board. These units feature switch selectable gains with an input impedance of 1 Mohm (the output impedance of the force transducer was 350 ohms nominal while that of the accelerometer was 1500 ohms nominal) thus providing no-load to the sensors. A dc-offset adjustment is also available as well as a bandpass filter. Figure 1 describes a block diagram of the overall instrumentation system. All cables used to connect transducers to the amplifiers and A/D conversion system were shielded and ground loop currents were eliminated.

CALIBRATION

Each system used was calibrated and checked against the manufacturer's specifications. All were found to be well within specifications.

3SPACE ISOTRAK Positioning System

The linearity and resolution of the Isotrak unit was verified using Melles Griot optical positioners featuring 20 micron resolution which is well below the 0.762 mm resolution of the Isotrak. Sensor and source were mounted on non-metallic rods so as to be free of the metal effects of the positioners. Adequate time was given between each reading to allow for any oscillations in the rods due to the movement. Linear regression analysis was performed on each axis (translational and rotational). Worst-case fit occurred for the x-axis translation with a correlation coefficient of 0.9754. All other axes possessed 0.99 correlation or better.

A.L. Design Model ALD-Micro-1 Load Cell

The load cells are delivered with a very detailed analysis of their specifications. Repeatability and linearity data are provided. We verified the specifications using an Ohaus mass calibration set and a Keithley Model 196 Digital Multimeter (DMM) featuring 5-1/2 digit accuracy. The Model 196 is capable of 100 nV resolution and features an input impedance of over 1 Gohm for the load cell range of interest. The load cell was powered with the temperature compensated supply. The cells were tested over their full scale range and were found to have correlation coefficients exceeding 0.999.

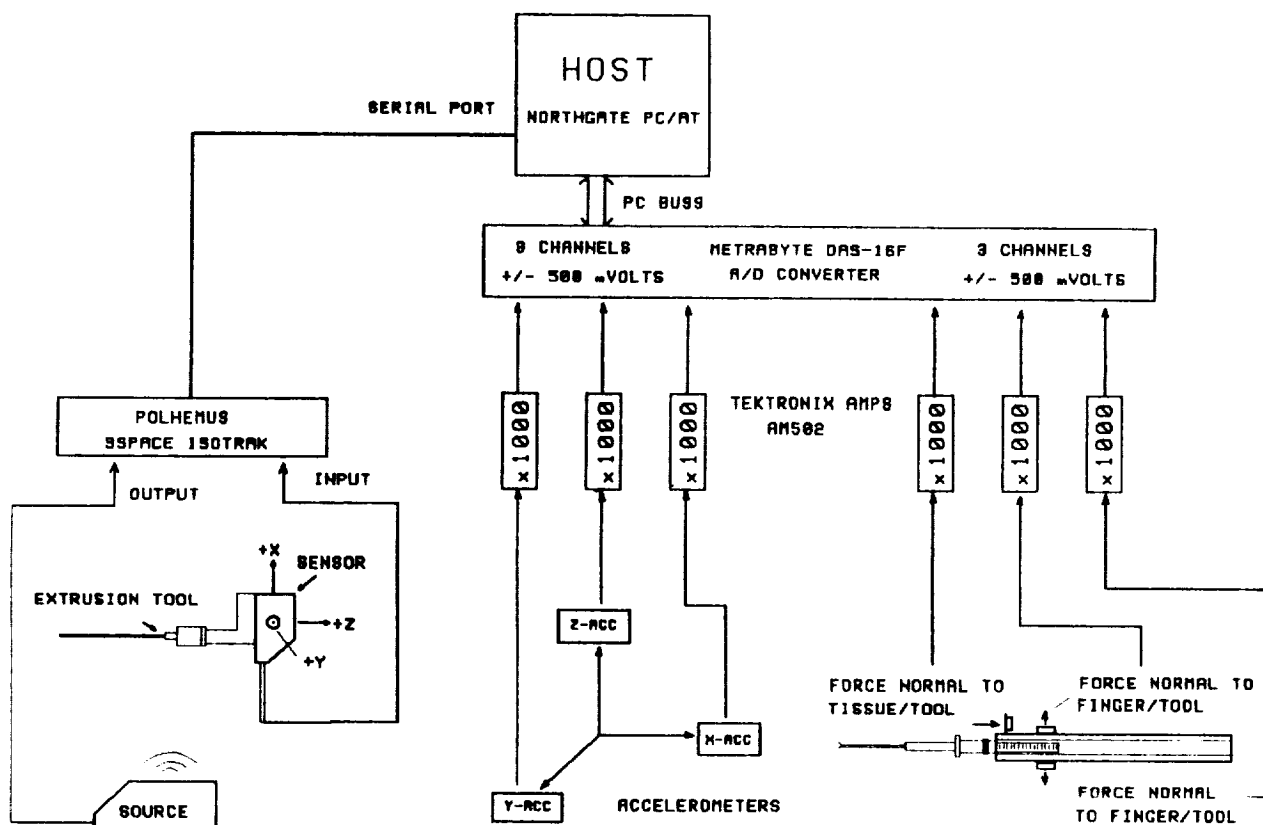


Figure 1. Data Acquisition System.

Vibro-Meter CE505M201 Accelerometer

Vibro-Meter also supplies test data for the accelerometers which includes a noise floor figure, sensitivity and a frequency response graph. At the time of this writing, we had no accurate means of verifying the specifications of the accelerometer. Therefore, those specifications were accepted for the present experiments. We plan to find a means to calibrate the accelerometers at a later date.

MetraByte DAS-16F A/D Converter System

The A/D system was calibrated using a temperature compensated battery source and the Keithley DMM. The range selected for conversion extended from -500 mV to +500 mV represented respectively by -2048 to +2047 digital levels. Linearity was verified to be within +/- 1 bit over the full-scale range.

METHODOLOGY

All data was recorded in actual eye microsurgery and thus sterile management of the transducers was followed. In all cases autoclaving was avoided for fear of damaging the semiconductor components within each

sensor. Instead, sterile plastic covers were used to isolate the sensors from the sterile field. Each procedure was designed with both the surgeon and operating room technician providing input regarding sterilization .

Position Measurement

Measurement of position included both the hand and two common instruments found in ophthalmic microsurgery: the straight extrusion tool and the Sutherland Scissors. During all three measurement cycles, the Isotrak unit was in the data averaging mode with the serial communications rate set to 4.8 KBaud. This resulted in a sampling time of approximately 140 msec (about 7 Hz). The host data capture algorithm was written in Microsoft C and basically captured the data in an array while periodically writing it to a hard disk file. At the beginning of each experiment, the source-to-sensor alignment was set allowing data collection from a (0,0,0) orientation. The data was then analyzed using Quattro, a spreadsheet program. Results and discussion of this analysis are presented later in the paper.

For the hand measurements the sensor was inserted in the sterile plastic bag and placed under the surgeon's sterile gloves. The gloves provided a two-fold purpose by further isolating the sensor from the sterile field and providing a very stable mount of the sensor. The data cable for the sensor was routed under the surgeon's gown and over his shoulder to the Isotrak electronic unit. The Isotrak source was mounted approximately 65 cm above and to the right of the sensor on an aluminum tripod. The source could not be placed closer to the sensor due to sterile field conditions. Source and sensor cables were separated and kept away from the host's CRT. Figure 2 describes the orientation of the x, y, and z-axes as mounted on the hand.

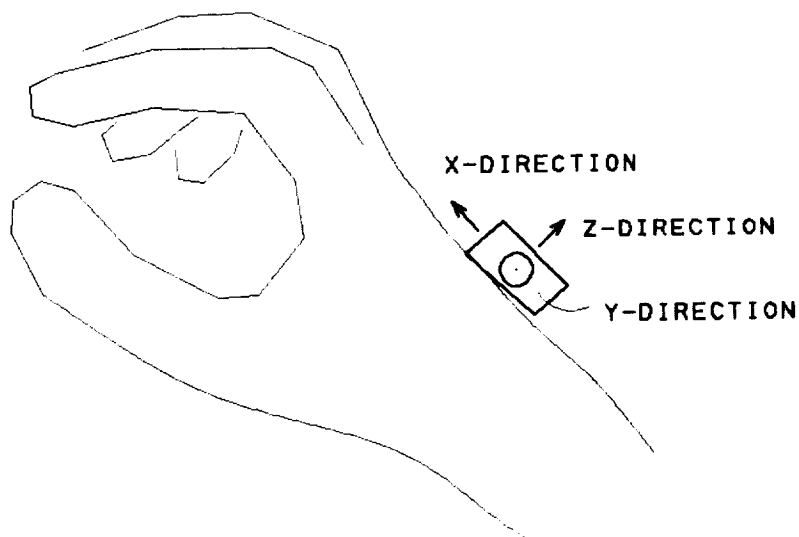


Figure 2. Hand Positioning Study: Magnetic Position Sensor Orientation

The straight extrusion tool does not require extremely precise movements, however, it's range of motion can be quite large as it is often times used to remove trapped gas bubbles within the eye chamber. The magnetic sensor was placed in a sterile bag and attached to the straight extrusion tool by means of a PVC right-angle support. This support fit into the handle of the tool and then provided a wide base to mount the sensor. The sensor was mounted to the support with sterilized tie straps and sterile tape. The data cable was again placed in a sterile bag and routed down the surgeon's arm. Figure 3 describes the mounting and sensor orientation on the extrusion tool.

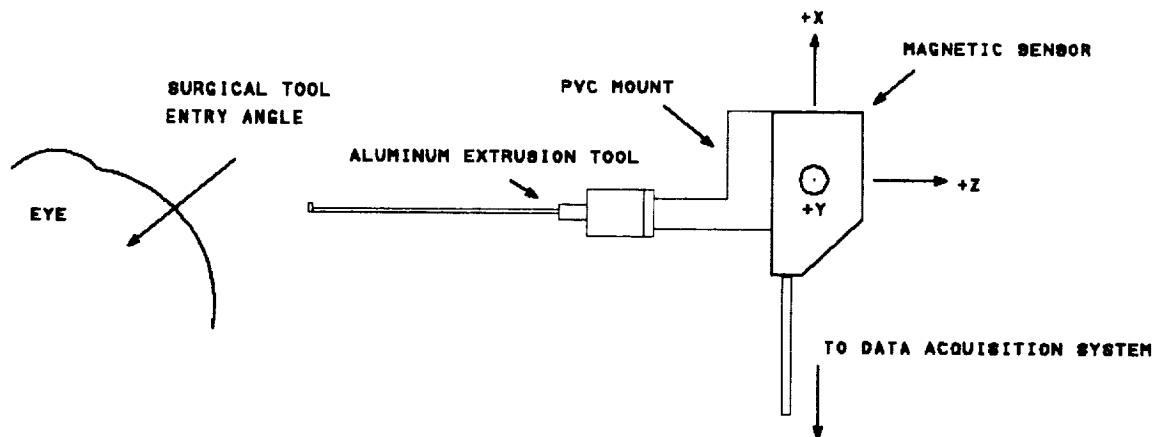


Figure 3. Magnetic Sensor Mounted to the Straight Extrusion Tool

The Sutherland Scissors is an instrument that requires precise manipulation of the tool tip. For example, scissors have become the primary method for most diabetic Epiretinal Membrane delaminations. This technique requires the blade to be parallel to the retinal surface and thus extremely small movements are required [2]. Figure 4 describes the sensor mounting. The scissors are aluminum and again the sensor was placed in a sterile bag and subsequently taped to the scissors handle. It must be noted that the sensor and data cable did impede some movement during surgery not allowing the recording of the full operating procedure. This occurred since the scissors are fairly long causing the cable to strike the operating microscope directly above the eye. However, maximum values defining the workspace were recorded.

Acceleration Measurement

Acceleration was measured in the x, y and z-axis directions for the hand only. The accelerometer was placed in a sterile bag and fitted under the surgeon's glove in much the same way as the position sensor with axis orientation shown in Figure 5. The power/data cable emerged at the junction of the glove and gown due to cable length limitations. The cable did not hinder the surgeons movements. Data was recorded for two different procedures: a forceps membrane peeling operation and a vitrectomy (removal of the vitreous). The forceps operation represents one of the most precise tool manipulations while the vitrectomy represents a wide range of motion. Both operations required the surgeon to remove the tool and re-enter yielding large acceleration values.

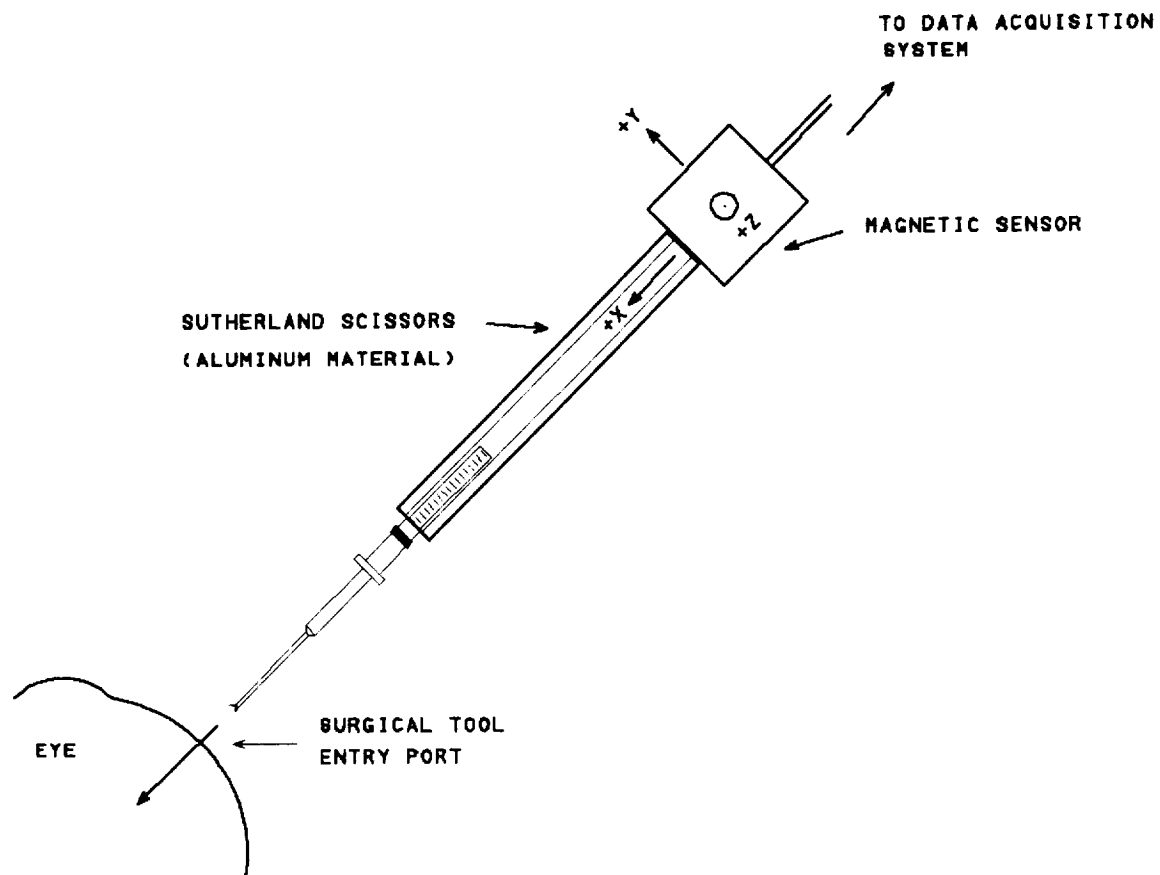


Figure 4. Sutherland Scissors Mounting and Sensor Orientation.

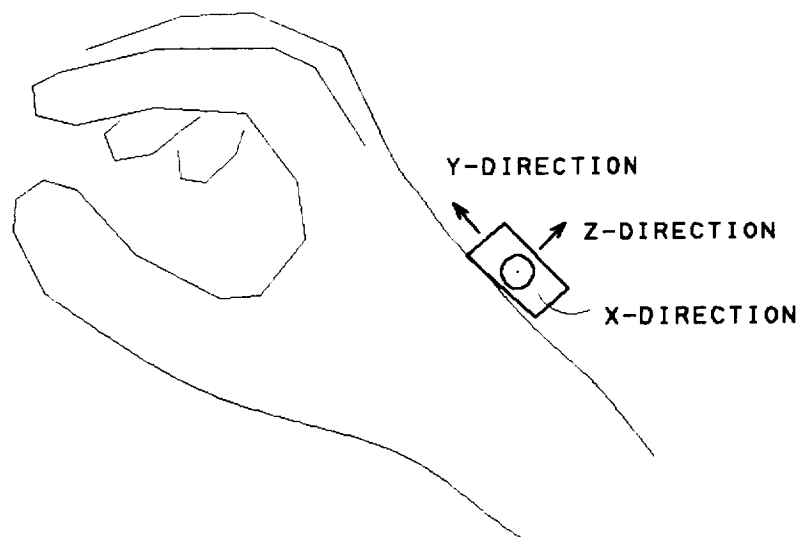


Figure 5. Hand Acceleration Study: Accelerometer Orientation

Force Measurements

Two force transducers were used to record force felt by the fingers at the perpendicular-to-tool interface and the perpendicular-to-tissue interface. Figure 6 describes the sensor mounting on the Sutherland scissors tool. This tool was chosen as it offers one of the most delicate operations due to the presence of the retinal surface. Force transducer 1 was mounted so as to measure tactile sense and the effect of tool weight and configuration on the proprioceptive sense. Force transducer 2 attempts to measure the force felt due to the tissue/tool interface. Both cells were mounted flat against the support structures and with the cell buttons accessible to the surgeon's fingers. The entire upper structure of the Sutherland scissors, the load cells and their power/data cables were placed in the sterile bag. The sterile scissors tip was attached by the operating room technician just prior to use.

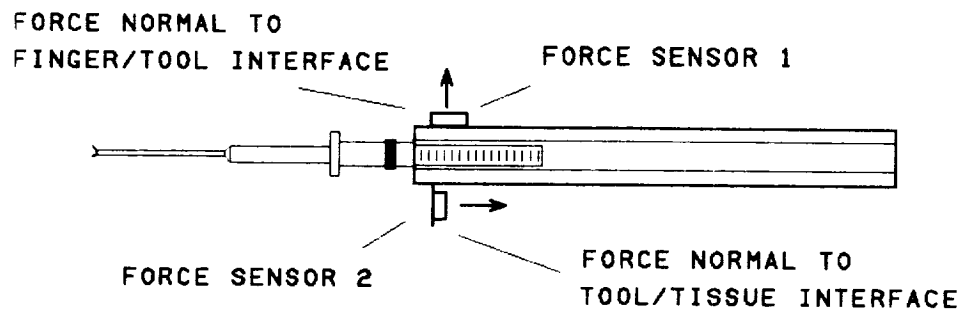


Figure 6. Force Transducers Mounted to Sutherland Scissors

RESULTS

In order to model the telemicrosurgery application various parameters of the microsurgeon's hand dynamics must be known. This work concentrated on determining the minimum and maximum values of position, acceleration and force. In order to find these values large amounts of data were recorded and subsequently plotted. Due to the page limitation of the proceedings, these plots describing typical performance are omitted. Interested individuals may request this data from the Center for Engineering Applications. We report here those maximum and minimum values which the SMI and manipulators must outperform.

Position or Workspace

On examining the workspace for vitreoretinal microsurgery it appears as

a cone within and outside the eye. This is due to the pivot point at the incision. Our data describes the cube that encapsulates this cone at the outside of the eye and therefore represents the workspace of the micromanipulator. Minimum and maximum values are shown below for the two tools studied.

SUTHERLAND SCISSORS - WORKSPACE DATA

	POSITIVE TRANSLATION (cm)	NEGATIVE TRANSLATION (cm)	CLOCKWISE ROTATION (degrees)	COUNTERCLOCKWISE ROTATION (degrees)
X	2.27	-0.11	42.00	0.00
Y	5.65	-2.54	9.99	13.47
Z	6.96	-1.33	20.16	79.45

STRAIGHT EXTRUSION TOOL - WORKSPACE DATA

	POSITIVE TRANSLATION (cm)	NEGATIVE TRANSLATION (cm)	CLOCKWISE ROTATION (degrees)	COUNTERCLOCKWISE ROTATION (degrees)
X	2.58	-2.00	79.38	23.89
Y	0.42	-1.35	18.11	7.44
Z	0.99	-0.65	4.53	114.61

TYPICAL WORKSPACE - OPHTHALMIC MICROSURGERY (Orientation defined by Sutherland Scissors Sensor Mount)

	TRANSLATION (+ to -)	ROTATION (CW to CCW)
X	2.38 cm	103.27 °
Y	8.19 cm	119.14 °
Z	8.29 cm	25.55 °

Acceleration

Acceleration data represents hand acceleration and not necessarily tool acceleration.

	PROCEDURE: FORCEPS			PROCEDURE: VITRECTOMY		
	X-AXIS	Y-AXIS	Z-AXIS	X-AXIS	Y-AXIS	Z-AXIS
MAX +	0.82 g	0.52 g	0.63 g	0.83 g	0.26 g	0.23 g
MAX -	0.10 g	0.55 g	0.49 g	0.11 g	0.36 g	0.28 g

Force

Force was analyzed for maximum values to determine SMI conditions as well as average force to study loading of the proprioceptive senses. Graphical data indicates that the tool/tissue sensor recorded globe deformation as the tool worked against the incision. We are in the process of estimating the force due to internal eye pressure and tissue. With this data we feel we can estimate the force seen near the tool tip as it encounters tissue. Regardless of the exact force the sensor measured, it still represents the resistance felt by the surgeon.

	FINGER/TOOL: FORCE SENSOR 1	TISSUE/TOOL: FORCE SENSOR 2
MAXIMUM	16.20 grams	42.68 grams
AVERAGE	13.19 grams	31.13 grams

DISCUSSION AND FUTURE DIRECTION

The results shown here will aid the CEA in development of the Bimanual Telemicro-operation Test Bed which serves as a first step toward increasing dexterity of the microsurgeon and providing for remote surgery capabilities. Results were within the ranges we expected. For example, the typical eye is about 2.54 cm in diameter and the maximum value we recorded for entry and exit (X-direction) of the tool was 2.38 cm. Y and Z directions are listed at 8.19 and 8.29 cm respectively, and taking into account the approximate 4:1 leverage amplification of the tool (Sutherland scissors), these values become 2.05 and 2.07 cm. Forces measured were close to preliminary data recorded by using a micro-beam scale and having the surgeon press the tool against the scale until he "feels" similar resistance as in the eye. The preliminary measurement was very subjective but was confirmed by two surgeons.

During the development of the test bed, a down-sized surgeon/machine interface will be developed which we believe will aid NASA in solving the dexterity problem encountered in pressurized spacesuits. We are currently working with Dr. Bill Hamel of Oak Ridge National Laboratories in the analysis of the kinematics and coordinate transformations needed for the interface.

As a continuation of this paper's work we are currently developing a measurement system to correlate video images of the surgeon's hand movements to the magnetic positioning system output. We are also developing a method to measure the force and torque felt during surgery in all six degrees-of-freedom.

REFERENCES

- [1] Gabriel, K., Jarvis, J. and Trimmer, W., "Small Machines, Large Opportunities: A Report on the Emerging Field of Microdynamics," Report of the Workshop on MEMS Research, 1988.
- [2] Charles, S., *Vitreous Microsurgery*, Williams and Wilkins, 2nd Edition, 1987.